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# Inductive Charging of Pulse Lines in 0.1 to 1.0 MJ Range Using Foil Fuses Staged with Explosively Actuated Switches

D. Conte, R. Ford, W. H. Lupton, J. D. Shipman, Jr.,
P. Turchi and I. M. Vitkovitsky

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March 1978

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The use of inductive storage techniques to replace the conventional high voltage sources, such as Marx generators, for the charging of high voltage transmission line pulse generators (i.e., capacitive loads) is discussed. The proposed opening switch system consists of exploding foil fuses staged with high explosive actuated switches. The low resistance of the explosive switches in the closed stage allows the inductive store to be charged at relatively slow rates without significant energy loss. Upon opening, current is commutated to the foils which rapidly explode next page

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**20. Abstract (Continued)**

**to generate the inductive voltage necessary to charge the load. A detailed analysis of fuse performance in the basic inductive storage circuit is presented using emperically obtained data on the resistivity vs. dissipated energy characteristic of vaporized aluminum foils. The results are used to outline the design of inductive storage systems for pulse charging capacitors to 1 MV at energies from 100 to 1000 kJ, with risetimes of 2 to 10 μsec ($10^{11}$ to $10^{12}$ W rate) and efficiencies of 20 to 65%.**

microsec

10 to the 11th power to

10 to the 12th power

CONTENTS

## I. Introduction

Inductive storage, because of its capability of storing energy at high densities, is an effective technique for designing compact high power pulsers. In particular, this technique can substantially reduce the size and cost of the high voltage charging systems for high energy, transmission line pulse generators. The basic inductive storage circuit for this application is shown in Fig. 1. The capacitive load represents either a water or oil dielectric intermediate storage capacitor or pulse forming line conventionally used in the generation of terawatt pulses.[1] Although the circuit is simple, its successful operation in megavolt systems with energies in excess of 100 kJ will require further development of the individual components. Some of the high energy, high voltage problems associated with the current source, the inductive store, and the charging of capacitive loads have been addressed by Trost et al[2], Robson[3], and Liebing[4], respectively. Perhaps the most difficult element to design is the opening switch. This device must have low loss in the closed state so that energy is not lost while charging the inductor, must have an opening time in the microsecond range, and must be able to hold off the voltage it generates (i.e., cannot restrike). The rapid opening time is not only necessary to generate a high voltage, but especially essential in water dielectric high power pulse line design because of the time dependent breakdown characteristics of water.[5] The following three sections of this report present data for the design of an opening switch system consisting of exploding foil fuses staged with high explosive actuated switches. The components for this system have already been tested at levels which indicate that microsecond operation at 1 to 2 MV is feasible.[6] Based on these results and recent developments in the design of compact current sources,[7,8] the remainder of the paper presents an analysis of the performance

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of inductive storage systems for pulse charging capacitors to 1 MV at energies from 100 to 1000 kJ, with risetimes of 2 to 10 μsec ($10^{11}$ to $10^{12}$ W rate) and efficiencies of 20 to 65%.

## II. Pulse Line Charging by High Voltage Fuses

An exploding wire or foil (fuse) is one of the most effective devices for fast interruption of current where the ability to hold off high voltage is also required. These elements have exhibited submicrosecond opening times, high current capabilities, voltage multiplication factors[9] exceeding 20, and voltage levels up to 2 MV.[10] Although many materials, geometries and surrounding mediums can be used in fuse designs, the fuse development at NRL has concentrated on the use of flat aluminum foils immersed in water or hydrogen peroxide. The operation of these fuses appears to be dependent on a combination of chemical and thermal effects which can be optimized[9] by an appropriate choice of the fuse thickness to width ratio. Fuse performance can be further improved by optimizing the foil shape in the region around the electrode contacts to insure simultaneous explosion of the entire foil.

Fig. 2 shows a schematic diagram of an experimental setup for charging a capacitive load, consisting of an 8 Ohm Blumlein pulse line with approximately 20 nF of capacitance, by a single fuse. Typical waveforms from this model are also given showing the current through the inductor, voltage across the fuse, and the Blumlein output pulse. This system has successfully charged the pulse line to voltages of 550 kV by using a 100 cm long by 5.1 cm wide by 6.35 μ thick foil immersed in water. This represents an energy of approximately 3.0 kJ on the pulse line. The 50 nsec duration output pulse has a peak power of 3.8 x $10^{10}$W into a matched resistance load. These experiments furnished data on

the performance of fuses in low energy systems and provided a basis for the comparison between analytical predictions and experimental operation of inductively charged capacitors.

## III. Aluminum Foil Fuse Characteristics

In order to design a proper switch for pulse charging circuits such as described above, the intrinsic properties of the fuse must be known. The first property to be considered is the dynamic conductivity. It is reasonable to expect that the temperature dependent conductivity of the material is related to the energy dissipated in it. The energy dependence of the conductivity for exploding copper foils has been described by Di Marco and Burkhardt[11] for foils pressed in plastic insulation and by Benford et al[12] for foils under water. Benford mentioned that aluminum was also used but no data was presented for it. The Efremov Institute in the Soviet Union has reported[13] 500-fold relative resistance increases with evaporating aluminum foils.

Conductance and dissipated energy can be calculated from values of fuse current and open circuit voltage obtained during the evaporation of the fuse. These data were measured during the course of the underwater explosion of aluminum foil fuses. A schematic of the electrical driving circuit, the fuse parameters, and typical current and voltage waveforms are shown in Fig. 3. The current risetime was chosen to be approximately 250 μsec because the fuse element of an efficient inductive storage system would necessarily have a current risetime of one msec or less. The 250 μsec value places the data within a factor of five of the expected extremes for the current risetime. Analysis of these measurements results in a correspondence between the conductivity, $\sigma$, and energy density, W, as shown in Fig. 4. The plotting of this data in terms of energy density allows it to be scaled to the design of high energy systems.

The time dependent conductivity was found to be continually decreasing and reached a value of less than $10^3$ mho/m at the time the current became too low to measure. Conductivity values below $10^4$ mho/m were not shown in Fig. 4 because, in this range, the correlation with energy becomes increasingly unreliable. This is due to the possiblity of systematic error in the synchronization of current and voltage waveforms.

Examination of Fig. 4 shows that the conductivity is approximately a negative exponential function of energy density. The dashed line is a plot of the relation $\sigma = \sigma_o \exp(-2 \times 10^{-10} W)$. This formula is used to describe the fuse conductivity in subsequent design calculations. The point where $\sigma_o = 2.4 \times 10^6$ mho/m will be used to define the onset of the explosion (t=0).

Another important parameter of the fuse which must be taken into account is its time to explosion, $t_e$. Clearly, it must be long enough to permit energizing the storage coil from capacitors (or, alternatively, to permit recovery of the first switch when using two stage switching as discussed in Section IV below). Furthermore, the efficiency of energy transfer from the storage coil to a load capacitor will depend on the relative values of $t_e$ and the $(LC)^{1/2}$ time of the circuit. It is well known that the value of $t_e$ is inversely proportional to the square of current density. More precisely, $t_e$ can be determined from an "action" integral, $\int_0^{t_e} j^2 dt$ = constant. Maisonnier et al[14] have calculated the time to explosion of some metal foils. Assuming slow heating and neglecting losses, their result for aluminum foils is equivalent to an "action" constant of $4.9 \times 10^{16}\ A^2 sec/m^2$.

It will be found useful in subsequent analysis of the capacitor charging circuit to define a fuse characteristic time nearly equal to $t_e$ as $t_o = w_v \sigma_o / j_o^2$. Here $w_v$ is the energy density needed to explode the fuse and $j_o^2/\sigma_o$ is the

joule heating rate (per unit volume) at the onset of the explosion. This characteristic time is convenient to use since it is independent of the shape of the current pulse. It does not matter that the point corresponding to onset of explosion cannot be determined with precision. All that matters is that a point can be selected where the subsequent energy dependent conductivity is known. Once a point is chosen, it should be used consistently. Reference to Fig. 4 shows that appropriate values are $w_v = 2.5 \times 10^{10}$ $(J/m^3)$ and $\sigma_o = 2.4 \times 10^6$ (mho/m), so $t_o = 6 \times 10^{16}/j_o{}^2$ (sec). This characteristic time is only slightly greater than the time to explosion when the fuse is driven by a constant current. It is about 3/5 of the time to explosion when the fuse current is a quarter cycle of a sinusoidal wave.

A further important characteristic of the fuse is its voltage hold off dependence on electric field strength. If the field is high enough, the time dependent conductance reverses its normal decrease and instead increases so that the fuse current is not interrupted. Such events have been called restrikes and may be similar, in some respects, to dielectric breakdown in insulators.[15] Restrikes limit the usefulness of the fuse as a switching device. Salge et al[16] presented data on the maximum field strength as a function of $t_e$ for copper wires. This data shows that higher field strengths are permitted if the wires are under water. For the longer times, still higher fields result when the underwater wires are enclosed by polyethylene tubes. In all cases, smaller values of $t_e$ permit greater electric fields. Similar data for aluminum foils under water are not available. A reasonable assumption is that the time dependence of the maximum field is qualitatively the same.

High electric fields on the fuse are the result of either a high voltage being generated by the current through the decreasing fuse conductivity during

explosion or by an initially high field imposed by the external source (e.g., capacitor bank voltage). For the first case, it is easy to show that the field is dependent on the characteristic time of the fuse. At the onset of the explosion the field is $E_o = j_o/\sigma_o$. In terms of the characteristic time, $t_o$, the current density is $j_o = (w_v\sigma_o/t_o)^{1/2}$ and consequently $E_o = (w_v/\sigma_o t_o)^{1/2}$. When fuses are used as switching elements their electric fields must be held below some limiting value, $E < Emax$, where $E_{max}$ is the restrike electric field strength. Since $E_{max}$ is dependent on the time to explosion, normalizing this electric field limiting relationship by initial electric field provides a convenient ratio for applying it to the design calculations for pulse charging a capacitor (to be shown later):

$(E/E_o) < (\sigma_o/W_v)^{1/2}\, t_o^{\,1/2}E_{max}$, where E is the increasing electric field along the fuse. Salge's data for copper wires shows that as $t_e$ is made shorter, $E_{max}$ increases just slightly faster than $t_e^{-1/2}$, so $t_e^{\,1/2}E_{max}$ is almost a constant. For underwater fuses of aluminum foil, it will be assumed that $t_o^{\,1/2}E_{max}$ is a constant. Although the value of $E_{max}$ is unknown, it must be greater than the maximum field observed from successfully operating fuses. Thus a conservative value for the constant can be obtained from measurements such as described in Fig. 3 ($E_{max} = 5.25 \times 10^5$ V/m, $t_o = 6.2 \times 10^{-5}$ sec). From these values, a safe limit to be imposed on the fuse is $E/E_o < 40$. When more data becomes available concerning the electric field dependence and the maximum field, this limiting ratio will be increased.

## IV. Two Stage Switching

Due to their inherently high energy absorption, fuses cannot be employed in circuits where they must carry current for times greater than a few microseconds and yet still provide high energy transfer efficiencies. A technique

for circumventing this problem is to parallel the fuse with another opening switch[16] which does not require the extremely fast risetime, but does have low loss in the closed state (Fig. 5). This second switch is used to commutate the current into the fuse. As will be seen later, a commutation time of the order of 50 μsec or less is needed to maintain high system efficiency, so that devices such as circuit breakers, which typically have opening times of several milliseconds, cannot be used for this operation. Thus, commutation techniques, such as those being studied at NRL in conjunction with the development of an explosively activated switch,[17] must be employed. This switch is shown schematically in Fig. 6. It consists of a current-carrying, aluminum tube which is ruptured in many circular locations along its length by an explosion that drives the tube against steel cutters. The explosion is caused by the ignition of primer cord placed along the axis of the tube. Paraffin is used as the explosive-pressure transfer medium. The paraffin also serves to electrically insulate the ruptured edges. Modules of this device have been tested at voltages of 300 kV at 35 kA. Its resistance, measured before opening, is in the micro-ohm range and its opening/hold-off recovery time is approximately 50 μsec. These modules have been tested in series and parallel combinations to demonstrate that increased voltage and current levels can be handled by proportionately increasing the number of modules. It is anticipated that 1-m long switch modules can be extended to the 500 kV range at currents well in excess of 100 kA.

## V. Energy Transport

An analysis of energy transfer to a capacitive load from an inductive storage coil has been made using the experimentally determined switch characteristics. For this analysis, the circuit equations corresponding to the equivalent circuit of Fig. 1 were integrated numerically beginning at the onset of the

fuse explosion. (The shunt resistance associated with water capacitors, which is typically on the order of 1 k for most pulse forming lines, can be neglected without significantly affecting the results.) The time dependent fuse resistance in the equations was d termined from the conductivity formula $\sigma = \sigma_0 \exp(-2 \times 10^{-10} W)$ and the dissipated energy, W, calculated from fuse voltage and current. Numerical integrations were done for fuses of various lengths and cross-sectional areas. The cross-sectional area, s, is accounted for through the characteristic time ($t_0 \propto s^2/i^2$) defined earlier. For a fixed cross-section, the effect of fuse length, h, on the output voltage can be determined through either of the parameters $W_v/(Li_0^2)$ or $R_0 (C/L)^{1/2}$. Both of these are proportional to h. Here $W_v$ is the energy required to vaporize the fuse, $Li_0^2$ is twice the initial stored energy, and $R_0$ is the fuse resistance at t = 0.

The results of several calculations are presented in Fig. 7. The two solid curves show the peak capacitor voltage (expressed as the dimensionless variable $V(C/L)^{1/2}/i$) as a function of fuse length (represented by the dimensionless variable $R_0(C/L)^{1/2}$) for two values of the parameter $t_0/(LC)^{1/2}$. These two curves are decreasing functions of $R_0(C/L)^{1/2}$ for the regions shown because as the fuse length is increased a greater part of the initial stored energy is spent in vaporizing the fuse.

To avoid restrikes and permit the fuse current to be directed into the capacitor, the electric field of the fuse must be limited. In section III, a safe limit was shown to be $V/(R_0 i_0) = E/E_0 < 40$. This limit corresponds to the dashed straight line drawn in Fig. 7. Therefore only those parts of the calculated curves lying below this line correspond to fuses that are realistically useable. The dimensionless voltage used in Fig. 7 is the ratio of the peak capacitor voltage to the voltage that would result if a perfect (no-loss) switch were

used. More importantly, the square of this ratio is the energy transfer efficiency. Therefore the intersection of the dashed, limiting-field line with either of the solid curves corresponds to the maximum efficiency that can be obtained with that value of $t_o/(LC)^{1/2}$.

The above analysis can be applied to the problem of charging a pulse-line capacitance using two-stage switching with explosively driven switches and fuses. The opening time of the explosive switches determines the value needed for the characteristic time of the fuse. If values of the $(LC)^{1/2}$ charging time are assumed, then curves similar to those in Fig. 7 permit a determination of the optimum fuse parameters and the efficiency, $\eta_f$, of the fuse switching. The total efficiency, $\eta_T$, is determined by taking into account the energy dissipated in the explosive switches while they are transferring current to the fuse.

The parameters of systems which could charge a pulse line to one megavolt at energies of 100 kJ and k MJ are listed in Tables 1 and 2, respectively. In its present state of development, the explosive switch opens in 50 μsec. The first three lines of the tables correspond to $t_o$ = 50 μsec with the $(LC)^{1/2}$ time decreasing from 10 μsec to 2 μsec. The last three lines are for a fixed $(LC)^{1/2}$ time of 2 μsec and indicate the improvement that could be achieved if explosive switch opening times were reduced to 10 or 20 μsec through further development. The initial current listed in the tables refers to the current in the storage inductor prior to opening of the first stage switches. The last column, listing the number of exploding switches required, is divided into two sub-columns; the first column assumes the present state of development of the exploding switch module, having 200 kV, 100 kA specification, while the second column is based on a modest projection of the operating level of the switch. The 100 kJ systems of Table 1 require low to moderate currents, ranging from 26 to 270 kA. The number

of exploding switch modules remains low even for fast capacitor charge times. For the megajoule systems of Table 2, the required current increases substantially as the capacitor charge time decreases. The number of exploding switches also increases proportionately. In all cases, as the current increases and the charge time decreases, the effects of lead inductance and stray capacitance become significant. The systems must be designed to minimize or make use of these unavoidable elements (e.g., use lead inductance as part of the energy store).

The high currents required for the megajoule systems could be obtained from current sources with lower current output, such as the existing NRL self-excited homopolar generator,[7] by using a current step-up transformer to charge the storage inductor. The efficiency of the overall system, however, drops at least 75% because the energy must be transferred from an inductive storage to inductive load before charging the capacitor. This is not altogether an unfavorable situation because the homopolar generators are inherently high energy devices with energy storage much greater than 1 MJ easily available. This approach has another advantage in that it allows the primary or secondary of the transformer to be crowbarred at the instant the fuse vaporizes to prevent the reverse step-up action of the transformer from applying an extremely high voltage to the source. If the pulse line were charged to 2 MV (with the load capacitance decreased by a factor of four and the storage inductance increased by a factor of four), the required current would decrease by a factor of two. The net result would considerably ease the current requirement. The number of exploding switches needed would remain about the same because the same amount of power is transported.

## VI. CONCLUSIONS

This analysis shows that inductive storage for pulse charging capacitors in the 100 kJ range, including those based on use of water dielectrics, can be

constructed using present technologies. Operation of the fuse at the megavolt level must still be demonstrated. Operation at 2 MV or greater voltage is desirable in order to lower the capacitance to more reasonable values. When megajoule systems are considered, not only must the operational level of the fuse be increased, but also more development on the first stage switch is desirable to limit the number of devices necessary.

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TABLE 1. PARAMETERS FOR 1MV, 100 kJ System
LOAD CAPACITANCE 0.2 μF

| $t_o$ (μs) | $(LC)^{1/2}$ (μs) | L (μH) | $\eta_F$ | $\eta_t$ | $i_o$ (kA) | No. of Switches (200kV) (100kA) | (500kV) (200kA) |
|---|---|---|---|---|---|---|---|
| 50 | 10 | 500 | .70 | .65 | 26 | 5 | 2 |
| 50 | 5 | 125 | .53 | .48 | 66 | 5 | 2 |
| 50 | 2 | 20 | .25 | .20 | 270 | 15 | 4 |
| 20 | 2 | 20 | .53 | .48 | 165 | 10 | 2 |
| 10 | 2 | 20 | .70 | .65 | 130 | 10 | 2 |

TABLE 2. PARAMETERS FOR 1MV, 1MJ System
LOAD CAPACITANCE 2.0 μF

| $t_o$ (μs) | $(LC)^{1/2}$ (μs) | L (μH) | $\eta_F$ | $\eta_t$ | $i_o$ (kA) | No. of Switches (200kV) (100kA) | (500kV) (200kA) |
|---|---|---|---|---|---|---|---|
| 50 | 10 | 50 | .70 | .65 | 265 | 15 | 4 |
| 50 | 5 | 12.5 | .53 | .48 | 660 | 35 | 8 |
| 50 | 2 | 2 | .25 | .20 | 2720 | 135 | 28 |
| 20 | 2 | 2 | .53 | .48 | 1650 | 85 | 18 |
| 10 | 2 | 2 | .70 | .65 | 1325 | 70 | 14 |

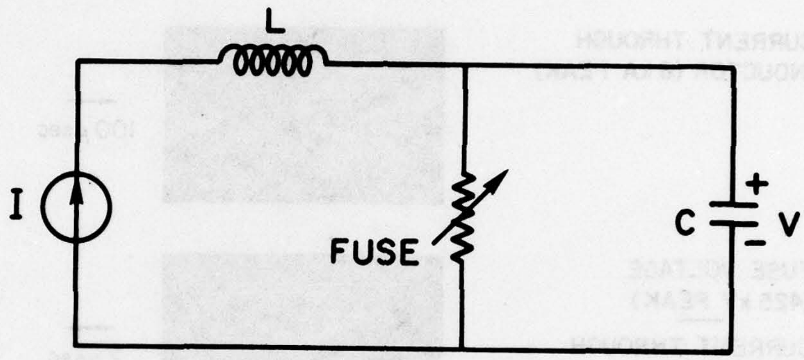


Fig. 1 — Basic inductive storage circuit with a capacitive load

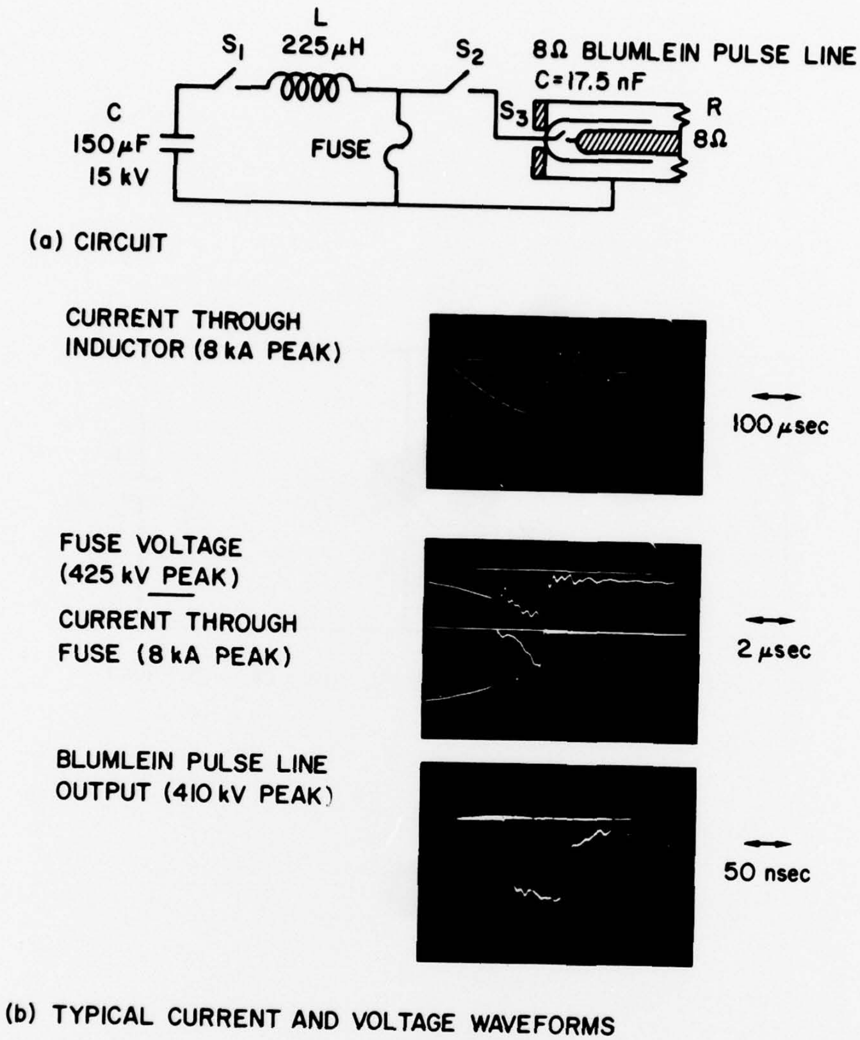


Fig. 2 — Inductive charging of a Blumlein pulse line using an exploding foil fuse switch

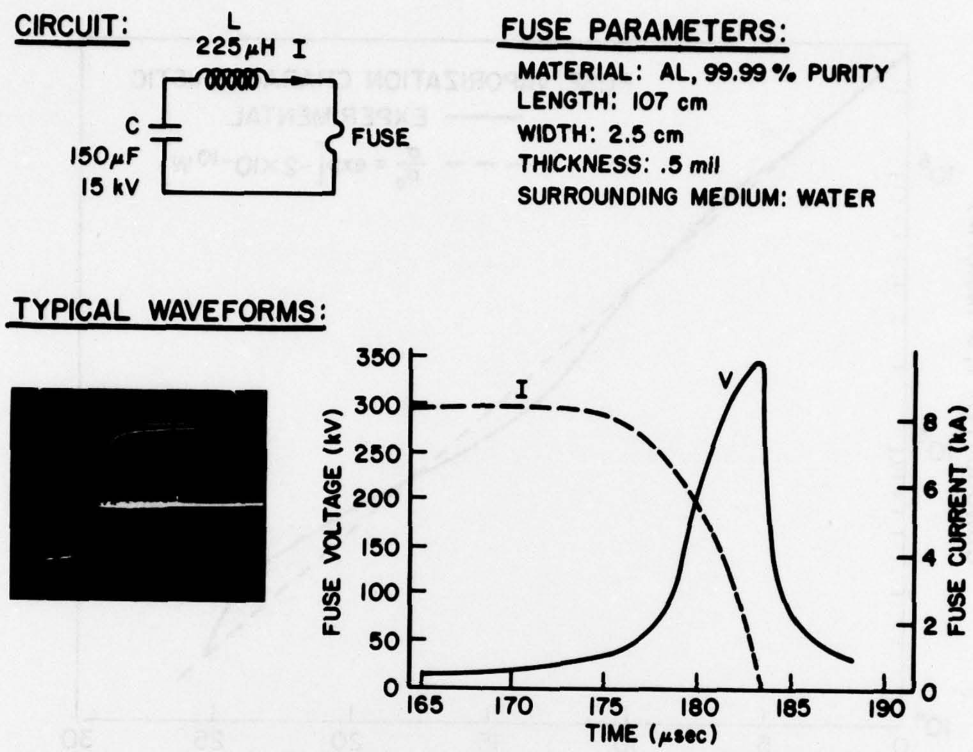


Fig. 3 — Test circuit and typical parameters and waveforms for foil fuses

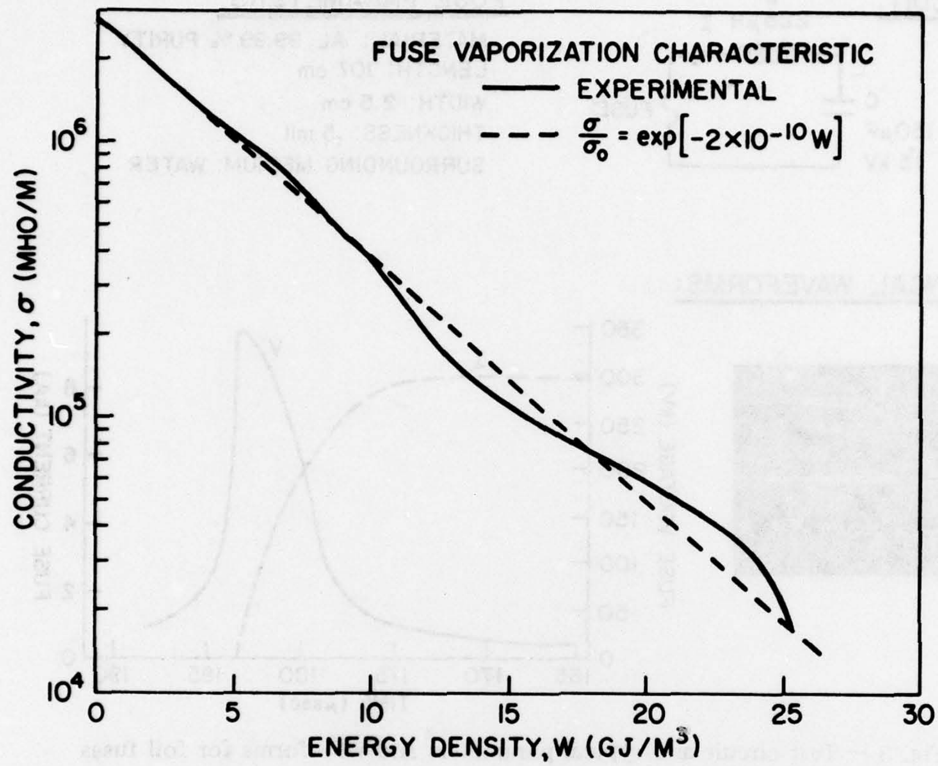


**Fig. 4 — Conductivity vs. energy density relationship for foil fuses operated in the test circuit of Fig. 3**

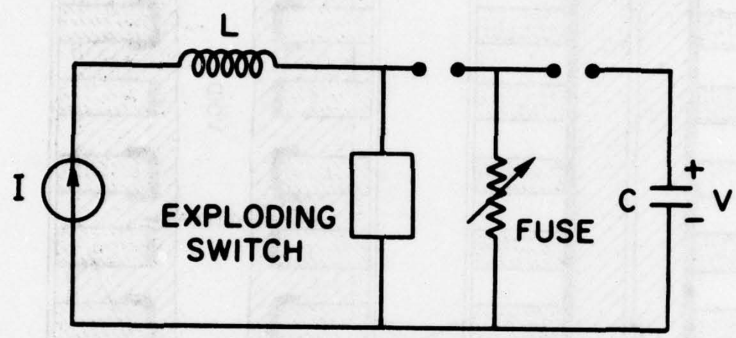

Fig. 5 — Capacitively loaded inductive storage circuit with two-stage switching

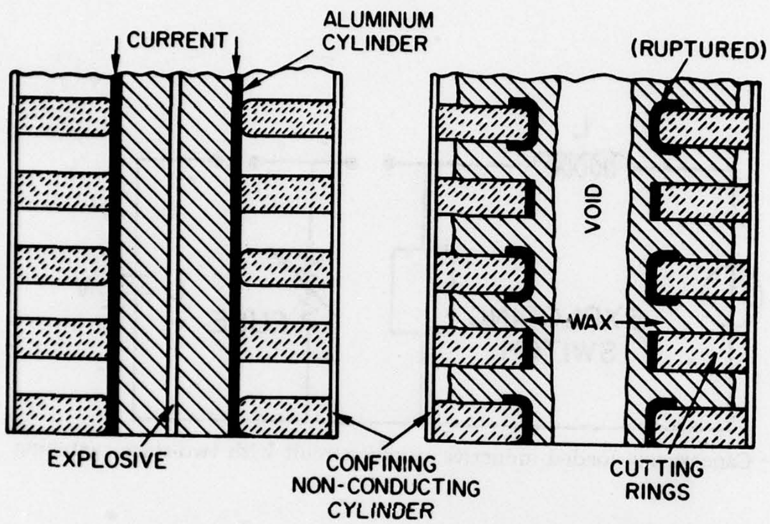


Fig. 6 — Schematic longitudinal section of the explosively actuated switch showing the switch before opening and in the fully opened state

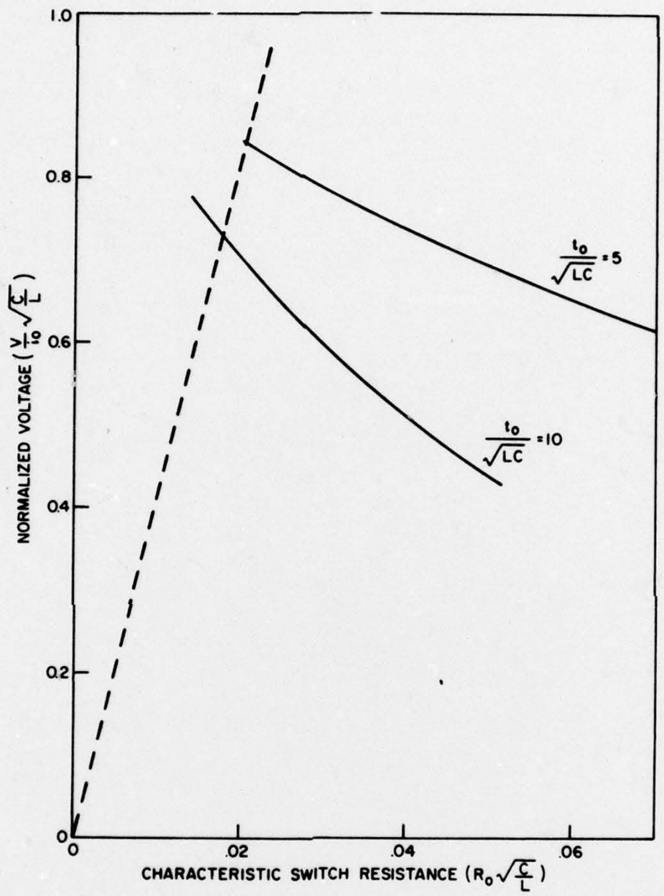


Fig. 7 — Peak value of capacitor charge voltage, in units of $i_0(L/C)^{1/2}$, as a function of fuse length, expressed by the parameter $R_0(C/L)^{1/2}$. The dashed line represents the limiting electric field permitted on the fuse.